

GROOVING FACTORY – BOTTLENECK CONTROL IN PRODUCTION LOGISTICS THROUGH AUDITORY DISPLAY

Revealing Work Content Overloads

Katja Windt

Michael Iber

Jacobs University Bremen gGmbH
School of Engineering and Science
Workgroup Global Production Logistics
P.O. Box 750 561, 28725 Bremen, Germany
k.windt@jacobs-university.de

Jacobs University Bremen gGmbH
School of Engineering and Science
Workgroup Global Production Logistics
P.O. Box 750 561, 28725 Bremen, Germany
m.iber@jacobs-university.de

Julian Klein

Institute for artistic research / Radialsystem V
Holzmarktstrasse 33
D-10243 Berlin, Germany
JulianKlein@artistic-research.de

ABSTRACT

Grooving Factory is the name of an interdisciplinary research project in the fields of production logistics engineering and auditory display. It aims to reveal bottlenecks in industrial productions and to improve the achievement of logistic targets by using sonification in production planning and control (PPC). Since data sets derived from production processes are time related, processes in production can be displayed as oscillating complex sounds, e.g. via additive synthesis. In this study, the feedback data of operations at 33 workstations of a circuit board manufactory served as a model for auditory display. The workload of the workstations was compared to their actual performance, which indicated their work in process (WIP) level, i.e. the balance of their input and output. The results of the auditory display were compared to WIP related bottlenecks identified by the bottleneck oriented logistic analysis including logistic operating curves. The research project includes the development of a new PPC method realized as a prototype in a software tool.

1. INTRODUCTION

1.1. Complexity of logistic targets

The analysis of different types of bottlenecks in the production workflow [1] is a basic principle in preposition to the parameter setting and application of production planning and control methods. These bottleneck types relate to the four logistic main targets, which include the achievement of short throughput times, high delivery reliability, adequate degree of capacity utilization and low level of work in process (WIP). Some of

these targets are contradictive and the identification of an ideal balance – which comprises the best possible achievement for the privileged target with the least drawbacks on the remaining targets - has become a highly complex task according to the increased requirements of flexibility and product variability in the global market.

1.2. Auditory Display and complex data

As a fairly young discipline at first defined in 1992 [2] auditory display is the non-speech acoustic representation of information within the human hearing range. One of its main features is the identification of single events in complex data, which would get lost in methods using rough resolutions like graphic displays or averaged calculations. In scientific fields such as space physics or stock market analysis, auditory display has been proved as a superior analysis tool in certain test arrangements. The research for an analysis tool based on auditory display to cope with the complexity of logistic data therefore seems a promising approach, especially since (once established) auditory displays provide results very quickly.

1.3. State of the art

The more it is surprising that apparently there have been only very few research projects in the field of production logistics involving auditory display: In the so named ARKola project, Gaver, Smith et al [3] developed a simulated soft drink factory, which consisted of an interconnected series of nine machines, eight of which were under user control. The processes of the machines were displayed by auditory icons representing the semantics of the specific machines, e.g. the

bottle dispenser producing the sound of clanking bottles. These sounds were audible to all users to give them a forecast of what to expect as well as a report on the impact of their actions.

A further approach was conducted by Alické [4]: According to him both, music and logistics rely on the order of sequences and in logistics, deviations from the sequencing rule “first in first out” (FIFO) of orders waiting in front of a machine influence the length of the lead time. He assumes that logistics can learn from musical principles and claims that there must be a common line between aesthetics and functionality. As an example Alické links the logistic processes of a container terminal to a given piece of music, “Satin Doll” by Duke Ellington, and compares patterns of melodic motives and logistic sequences. In spite of this interesting approach, Alické does not complete his research by developing a method for production planning and control.

Whereas the ARKola project emphasized on interactive aspects of Auditory Display and Alické's approach focused on arguable theses about the portability of musical structure for general purposes, this project tackles a third route, which is more related to approaches based on non-linear dynamics [5] investigating the phenomena of oscillation and synchronization.

1.4. Research targets

The overall target of the project is the development of a production planning and control method for workflows in production logistics based on auditory display. To accomplish this, a methodic transfer of production based data into auditory display has to be explored and methods to identify process related bottlenecks have to be investigated and established. The results will be compared with the ones obtained from the Bottleneck Oriented Logistic Analysis (BOLA) [6]. This comparison will also serve as a first validation step for analyzing production logistic data based on auditory display. Since there has been no fundamental research yet combining logistics engineering and auditory display, the setup of the project, which includes the development of prototyping software, started by very basic means to be sufficiently flexible to adjust to upcoming results. This included impulse based and sinusoidal based sonifications as well as several mapping strategies [7].

Section 2 of this paper introduces the data set used and gives insight into the BOLA. Section 3 gives general considerations about the mapping of production data to auditory display, which will be specified in Section 4 on the practical experience. Section 5 gives insight into the actual results of the auditory display based on the exposure of work content. Section 6 concludes the state of research and provides an outlook on future steps.

2. BOTTLENECK ORIENTED LOGISTIC ANALYSIS

2.1. DATA SET OF CIRCUIT BOARD MANUFACTORY

The data set chosen for the research originates from a circuit board manufactory (figure 1).

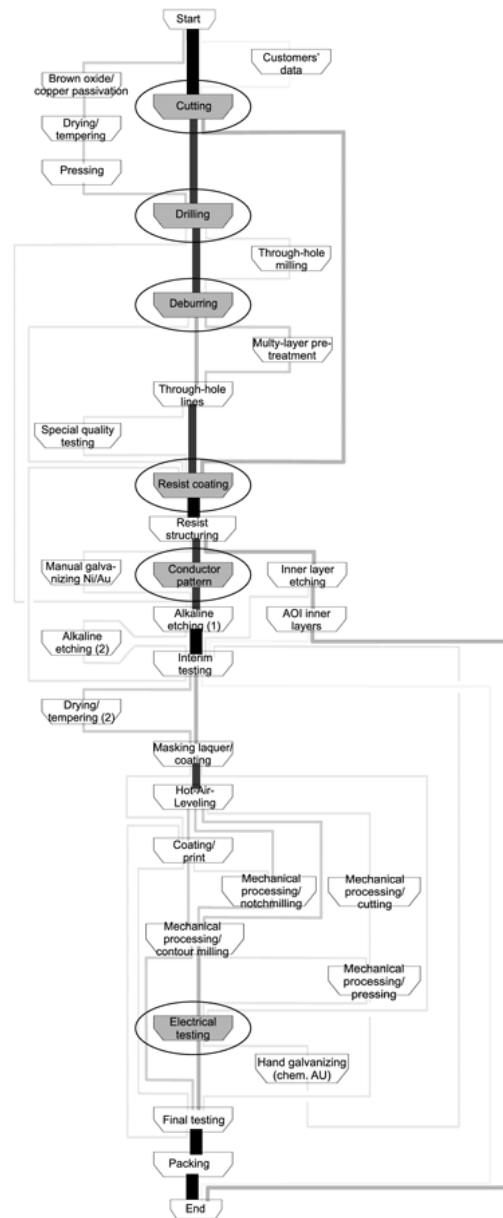


Figure 1: Workflow of circuit board manufactory. The individual workstations are displayed as funnels. Encircled workstations are bottlenecks identified by BOLA [6].

It monitors the workflow of an evaluation period of five month representing the processing of 4270 orders, each of which running through up to 31 operations at different workstations. The recorded data include information about the individual workstations with their daily capacities, order related information including the lot size of orders, as well as operation related data like operation sequence, work content, end of operation, or technology dependent waiting time. The

operational feedback data was monitored on a timely precision in seconds.

The motivation to select precisely this data set was that it has been extensively analyzed and documented by Peter Nyhuis and Hans-Peter Wiendahl [6] as an example of an application of Bottleneck Oriented Logistic Analysis including the Logistic Operating Curves Theory (LOC). The results derived from auditory display thus can be reliably compared and verified.

2.2. Bottleneck Oriented Logistic Analysis (BOLA) including Logistic Operating Curves (LOC)

The basic elements of the Bottleneck Oriented Logistic Analysis (BOLA) are the funnel model, which describes the input and output relation at individual workstations (figure 2a), and the 2-dimensional throughput element, which integrates the several processes before the operation and the operation itself including the setup time. The work content of the order (measured in the time needed for the operation) is represented by the height of the element.

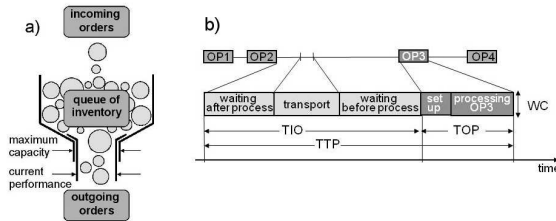


Figure 2: a) the funnel model describes the input/output relation at a workstation. b) the 2-dimensional throughput element describes the individual order at a workstation with OPx: orders, TIO: interoperation time [shop calendar days SCD], TOP: operation time [SCD], TTP: throughput time [SCD], WC: work content [h] [6].

The BOLA analyzes the production workflow from a order and resource oriented view (figure 3d). In a first step all individual workstations are statistically evaluated and ranked according to their mean output rate (= mean performance), their work-in-process level (WIP), as well as the due date reliability and the throughput times of the passing orders (3a, b).

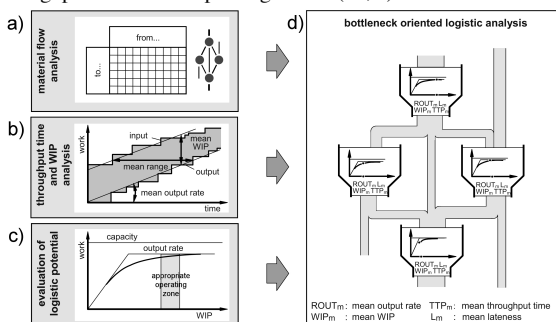


Figure 3: Bottleneck Oriented Logistic Analysis collects statistical information about all workstations (a), analyzes their throughput times and work-in-process-levels (b) and applies the Logistic Operating Curves Theory to balance parameters in respect to the target achievements [6].

That way workstations with high WIP can be identified and represents an initial step towards identification of bottleneck worksystems. Also known as inventory, WIP describes the balance between incoming and outgoing orders at a workstation, in other words: it is the composite work content (WC) of all orders at a workstation at a time. It is notable that the WC of incoming orders is measured by the time needed for processing (refer also to fig. 2b). This is due to varying durations of the operations needed for various product types and varying lot-sizes. WC is calculated in hours:

$$WC = (tp \cdot LS + ts)/60, \quad (1)$$

whereas tp is the processing time per piece for the specific product type (in minutes), LS is the lot size (number of pieces in order) and ts is the setup time of the workstation (in minutes).

According to the funnel formula [6] high WIP causes long mean throughput times (which can be considered equal to the range in steady state systems) and therefore long delivery times in the workflow. A workstation with high WIP will consequently be identified as a WIP related bottleneck of first order. Too low WIP on the other hand results in a poor performance causing a utilization-related bottleneck. Therefore WIP should be kept at a safe minimum level (which in practice is 2.5 times the calculated ideal minimum WIP [6] level assuming that the worksystem is not outer margin) avoiding the risk of performance losses and at the same time keeping throughput times as short as possible. The appropriate operating zone can be calculated by the Logistic Operating Curves Theory [6], which indicates the influence of the respective parameters on each other (figure 4). Furthermore, in BOLA one aim is to identify the so called order-related throughput time bottleneck work systems. Those work systems are in general characterized by a high number of orders being processed in combination with a long mean throughput time.

We will concentrate in the following as a first validation step of mapping production logistics feedback data to identify WIP bottlenecks as an overload situation of a work systems.

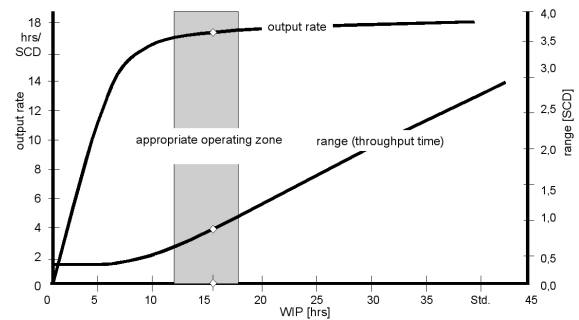


Figure 4: Ideal minimum WIP in relation to output rate and range [6]. A larger WIP will increase the throughput time without increasing the output rate significantly. Whereas a very low WIP would affect the performance significantly.

3. GENERAL CONSIDERATIONS CONCERNING DATA MAPPING IN AUDITORY DISPLAY

Operational feedback data of production processes is time-based as is any approach using auditory display. The immediate mapping of workflow data into sounds representing the length of the operations is self-evident. The content of the operations, i.e. the amount of pieces produced over the length of time can be represented as pitch:

$$f(i) = 1 / (TOP / x), \quad (2)$$

whereas i is the operation, f is the displayed frequency, TOP is the total operation time, x is the number of pieces produced, respectively the lot size.

The simplest possible scenario of a production chain is a linear arrangement of machines with operations of identical lot size and processing time without any waiting time in between (Figure 5a). In a representation as auditory display each workstation (OPx) produces tones of identical frequency (f). If on the other hand e.g. the second workstation (OP2) needed double the time for an operation, it would sound in half the frequency ($f/2$) and pause the sound of subsequent machines sequentially. Additionally, a queue will build up in front of OP2, the work-in-process level (WIP) will increase.

Figure 5b provides a solution to this problem by extending the second workstation to a group of two workplaces. Depending on whether the auditory display represents workstations or individual workplaces (where each workplace is represented by its own sound), it will either sound unison with the other workstations or the two workplaces of OP2 sound individually at the lower octave to the other workplaces. In both cases always all the workplaces will sound and there will be no queue.

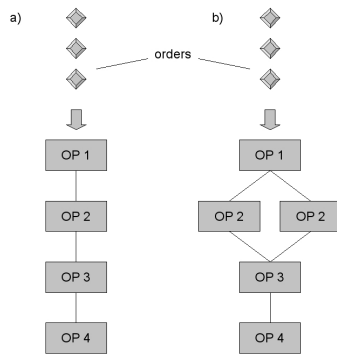


Figure 5: Examples of linear workflow, whereas OPx are sequential workstations.

Due to the large variety of product types and the complexity of routes all products may take in the workflow, “not sounding” of a workstation cannot be taken as an indication of bottlenecks. Pauses of workstations outside the main workflow, which are only used for special product types, happen regularly. The building up of queues in front of workstations is a much better indicator for WIP-related bottlenecks in this matter. It therefore should be most efficient to observe the waiting time

(interoperation time) of the individual orders before their processing, as well as the work in process (WIP) at the workstations.

4. DATA MAPPING APPROACHES

4.1. Development of software interface

The prototyping software developed for the auditory display of production data is based on a combination of the Pure-Data graphical programming language [8], which is used for the audio related parts (including additive synthesis and a variable surround setting between 1 and 16 output channels) and Python [9] for data reconditioning. It allows the auditory display of any combination of operations at workstations as well as the workflows of orders. Since sounds in the realm of the human hearing range are crucial for sonifications, several options are provided to adjust the data (figure 6) in this regard.

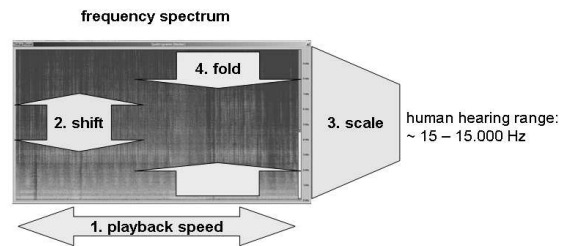


Figure 6. The software interface offers four options to arrange the frequency ranges to the human hearing range: 1st change of playback speed, 2nd shifting the frequency of a data section, 3rd linear and logarithmic scaling of all frequencies to human hearing range, 4th folding frequencies outside the audible range to their closed octave within the hearing range.

4.2. Occurrences of Inconsistencies in the Data

The research on fundamental data-to-sound mappings [7] revealed various inconsistencies of the data set with high time resolution. Accuracy of operational feedback data is a known problem in logistic analyses. Although there have been many improvements in the last years, many recordings of operations are still executed by humans. The data set used by Nyhuis and Wiendahl for the BOLA was reduced to daily precision and does not contain any inconsistencies. Additionally it should be considered that BOLA relies in general on averaging values over an evaluation period of some weeks, and therefore detailed information just will be weighted. On the other hand it is one of the advantages of auditory display to be able to deal with complex data on a high resolute time scale and it is one of the targets of the project to explore, if analysis based on auditory display will lead to similar results but obtained (eventually) in faster time and offering potentials towards complexity driven analysis.

The unexpected sounding results of the software displaying on the high resolute time scale revealed that up to some 60 processes were registered simultaneously at individual workplaces, where only one process – displayed as a monophonic signal – was considered at a time, which is due to the workers at the workplaces use to collect several orders at once in order not to loose time. That required an integration of the conflicting parallel processed orders. Therefore the overlaying sections of the conflicting orders were compounded to so to speak “virtual orders”, which represent all pieces in process at a certain time span.

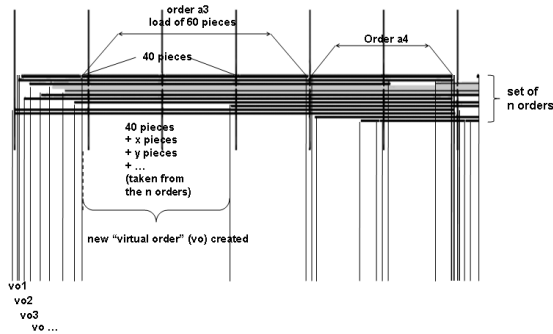


Figure 7: Overlaying orders are compounded in “virtual orders”.

This method also allows the display of interoperation times of orders in front of workstations, which naturally overlay, as well as their work in process (WIP).

4.3. Results of directly mapped auditory display

After most of the data inconsistencies concerning the reported schedule and operational sequences had been corrected experiments with sonifications based on the implemented direct mapping strategies, meaning that all workstations would display any of their operations, proved to be far too complex to spot out any irregularities in the production workflow. Also the consideration of single pieces produced appeared unrealistic, since no reliable production, setup and waiting times for the various product types could be derived from the data, further process related explanation on data entries is difficult to get. Therefore the idea of a high-resolution time scale was put on hold in favor to an investigation of feedback data with daily precision.

5. AUDITORY DISPLAY OF WORK CONTENT

In this setting not the inaccurately measured throughput time is taken into consideration as an indicator for the operation time but the WC, which relies on planned data. If the compound WC at a workstation is larger than its given capacity this may indicate a throughput related bottleneck. For this purpose the WC and the technical waiting time of an order are calculated backwards from the monitored output day taking the daily capacity of the workstation into respect. That means that, if WC is larger than the workstation’s capacity, it will be distributed over the according number of days. The adjusted software

integrates the WC of all orders at each workstation on a daily basis and allows the following options for display:

1. Absolute display of all operations at discrete workstations, pitch representing the WC in minutes.
2. Absolute display of WC overload at discrete workstations.
3. Relative display of WC overload, amount of overload in minutes represented by pitch.

The unfiltered sonification of the WC of all data sets (option 1) again sounds too complex to give any evidence of bottlenecks (sound example 1).

The auditory display of the relative WC overload (option 3) is more revealing. In a surround setting, where the workstations are panned between -45° and 45° according to their position in the workflow, a workstation around 0° can be spotted building up high frequencies as can be heard in sound example 2, which displays the overload of all workstations and 3, which displays the concerning workstation “multilayer pretreatment” alone (figures 8).

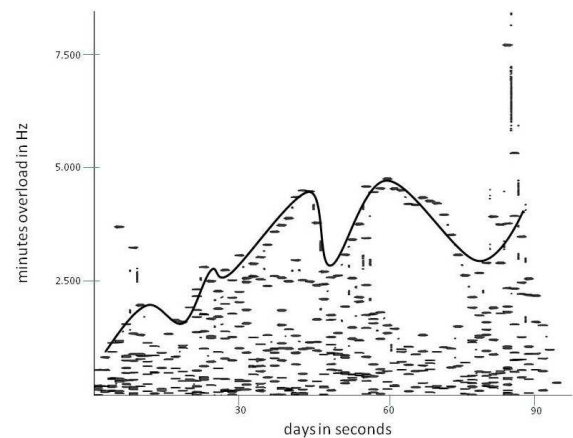


Figure 8: Visual representation with SPEAR [10] of auditory display of performance overload of all workstations over the evaluation period. In the auditory display, the constant peaks can easily be allocated to the workstation “multilayer pretreatment”.

Among the bottlenecks spotted by BOLA (figure 1), only the resist coating workstation displays overload worth mentioning in the sonification.

Another interesting, yet difficult to interpret result is the auditory display of the two succeeding workstations named “resist coating” and “resist structuring”. As can be heard in sound example 4 (figure 9), which again displays the relative overload, “resist structuring” (45° panning) “joins in” into the permanent overload of “resist coating” (-45° panning) with frequencies close to the ones displayed by “resist coating” synchronously most of the times with slightly higher pitches, i.e. higher overload. The fact that “resist structuring” only displays short sequences and then becomes mute again indicates that the workstation is capable of dealing with the workload over a specific period of time and therefore is not necessarily a bottleneck as defined by BOLA, which treats only longer periods of time. But it certainly can be considered a

short term hindering of the workflow, which impact has to be further investigated.

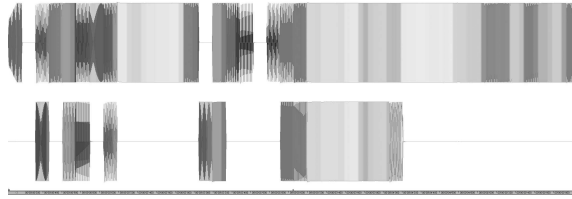


Figure 9: Resist coating (top) and resist structuring workstations visually displayed by Samplitude's comparasonics [11]. The grayscale brightness of the waveform represents the frequency.

6. CONCLUSION AND OUTLOOK

The actual study has not yet achieve the target to identify identically bottlenecks as the BOLA. But nevertheless these first results with auditory displaying the compound WC, which is an equivalent to the work in process (WIP) at the individual workstations raise a number of questions to be answered in the follow-up steps of research: 1st Why do most of the workstations, which are identified as possible bottlenecks by significant WC overload, differ from the ones identified by BOLA? 2nd What is the explanation behind the partial "joining in" into the melodic lines of neighbor workstations? How can their interplay be interpreted and manipulated? 3rd Is daily precision of data sufficient enough to investigate the impact of sequential changes of orders, which are executed e.g. to shorten setup times or to prioritize urgent orders? After these questions have been answered, the Grooving Factory should be capable not only to spot bottlenecks in a workflow immediately but also to precisely analyze the interferences of various scenarios in production planning and control.

7. ACKNOWLEDGMENT

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